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SYNTHESIS OF GENEVA MECHANISMS
WITH FINITE ANGULAR JERK

BY

JEFFREY EUGENE EDMISON, 1960 -

A THESIS

Presented to the Faculty of the Graduate School of the
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ABSTRACT

The primary purpose of this paper was to extend and implement earlier work on the development of Geneva wheel mechanisms with finite angular jerk. To ensure the angular jerk remained finite, each Geneva wheel was designed using curved slots. The curvature of the slots was defined by using standard motion programs. These standard equations forced the jerk to remain finite throughout the mechanism's motion.

To implement this curved slot concept, an interactive computer synthesis package, called GENSYN, was developed. It allows the user to design both regular and partially irregular Geneva mechanisms with a choice of three different standard motion programs. The display capabilities of GENSYN, including animation of the mechanism, offers a quick and convenient way to choose from several prospective designs.

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SYNTHESIS OF GENEVA MECHANISMS
WITH FINITE ANGULAR JERK

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ABSTRACT

The primary purpose of this paper was to extend and implement earlier work on the development of Geneva wheel mechanisms with finite angular jerk. To ensure the angular jerk remained finite, each Geneva wheel was designed using curved slots. The curvature of the slots was defined by using standard motion programs. These standard equations forced the jerk to remain finite throughout the mechanism's motion.

To implement this curved slot concept, an interactive computer synthesis package, called GENSYN was developed. It allows the user to design both regular and partially irregular Geneva mechanisms with a choice of three different standard motion programs. The display capabilities of GENSYN, including animation of the mechanism, offers a quick and convenient way to choose from several prospective designs.

INTRODUCTION

In situations where it is required to obtain an intermittent output motion from a continuous input motion, designers frequently select various configurations of the conventional Geneva mechanism. The conventional Geneva mechanism consists of a driving link with one or more pins which contact radial slots on the driven Geneva wheel. Chironis [1] provides an excellent description of the application of Geneva mechanisms to solve various practical mechanism design problems. Although these devices provide workable solutions, they also suffer from an undesirably high level of angular jerk at the beginning and end of the motion cycle. In many cases the useful operating speed range has been severely limited because of the jerk problem. Various approaches to reduce or eliminate the jerk have been proposed. For example, Dijksman [2] developed a series of four-bar linkage driven internal Geneva mechanisms which do not exhibit this problem. The follower was driven by a

roller appropriately mounted to the coupler link of a four-bar mechanism such that the center of the driving pin traces a specially shaped coupler curve which enables the driving pin to enter and leave the follower wheel along the straight-line portion of the coupler curve.

Jensen [3] suggests that a smoother Geneva indexing motion can be obtained by utilizing the cycloidal curve generated by a hypocycloid mechanism. The drive roller is mounted to the planet gear and traces a rectangular shaped cycloidal curve.

Fenton [4] proposed the use of two suitably matched Geneva wheels driven in series in order to eliminate the undesirable shock loadings typical of the basic Geneva mechanism. In the proposed mechanism, the rotary input crank drives the primary Geneva wheel. The secondary crank is rigidly connected to the shaft of the primary wheel, so that the primary wheel and the secondary crank rotate together. It can be arranged such that the input and output axes of the mechanism are coaxial, and the whole mechanism can then be placed between two aligned axes. However, the first or the intermediate Geneva wheel still experiences very large jerk at the beginning and end of its motion period. This may not be harmful in some machinery if the output shaft carries a large mass and the mass moment of inertia on the intermediate shaft is negligibly small.

Bagci [5,6] has studied index ratios for series connected Geneva mechanisms with single or multiple driving pins. His work includes cases of alternately driven slots and internal Geneva mechanisms. Bagci defines regular, partially irregular, and irregular types of Geneva mechanisms and his definitions will be followed here.

An alternate approach to those suggested earlier will be considered in this paper. Instead of using the conventional straight slots, the Geneva wheel will

be designed with curved slots which produce a controlled motion of the driven member when the driving member rotates at a constant angular velocity. Bin [7] examined this concept from a theoretical point of view and his work was extended and implemented by Edmison [8] in the form of an interactive synthesis program called GENSYN which will be described here.

THEORETICAL BASIS FOR GENSYN

A typical Geneva mechanism of the type to be discussed is shown in Fig. 1. The driving member contains two pins which contact the curved slots shown in the driven Geneva wheel. The driving member has dwell retainers which engage dwell arcs on the Geneva wheel to prevent rotation when the drive pins are not in contact with the curved slots. The locking device design can be considered after the slot design is finished.

Standard Motion Programs

It is common practice in cam design to select standard motion programs to move the cam follower from a position of rest (dwell) to another dwell position. Chen [9] presents three commonly used standard curves in normalized form as

$$S = \theta - \frac{1}{2\pi} \sin 2\pi\theta \quad (1)$$

$$S = 10\theta^3 - 15\theta^4 + 6\theta^5 \quad (2)$$

$$S = 35\theta^4 - 84\theta^5 + 70\theta^6 - 20\theta^7 \quad (3)$$

where S is the normalized displacement and θ is the normalized cam rotation angle ($0 \leq S \leq 1$, $0 \leq \theta \leq 1$). Eq. (1)-(3) are called respectively cycloidal, 3-4-5 polynomial, and 4-5-6-7 polynomial motion programs. When these equations are

differentiated three times with respect to θ , the jerk expressions are found to be

$$S''' = 4\pi^2 \cos(2\pi\theta) \quad (4)$$

$$S''' = 60 - 360\theta + 360\theta^2 \quad (5)$$

$$S'''' = 840 - 5040\theta^2 + 8400\theta^3 - 4200\theta^4 \quad (6)$$

Evaluating Eq. (4)-(6) at the locations $\theta = 0$ and $\theta = 1$ shows that finite values of jerk will exist for both the cycloidal and 3-4-5 polynomial with the jerk for the 4-5-6-7 polynomial being zero at both end points. Any of these motion programs would be an improvement over the jerk values present in a conventional Geneva mechanism employing straight slots.

Incorporation into Synthesis of Slots

In order to incorporate the more desirable displacement equations into the synthesis procedure, consider the arrangement shown in Fig. 2 where θ_2 is used to define the location of the driving pin and θ_3 is used to locate the driven Geneva wheel. Let the starting values of θ_2 and θ_3 , when the pin first contacts the slot, be designated as θ_{20} and θ_{30} respectively. Also let N define the integer number of slots on the Geneva wheel. Then the range of θ_2 and θ_3 for which contact will be maintained is given by

$$\theta_2 \text{ Range} = 360^\circ - 2\theta_{20} \quad (7)$$

$$\theta_3 \text{ Range} = 360^\circ/N. \quad (8)$$

Substituting back into Eqs. (1)-(3), the form becomes

$$\theta_3 = \theta_{30} - \frac{360^\circ}{N} \left(R - \frac{1}{2\pi} \sin 2\pi R \right) \quad (9)$$

$$\theta_3 = \theta_{30} - \frac{360^\circ}{N} (10R^3 - 15R^4 + 6R^5) \quad (10)$$

$$\theta_3 = \theta_{30} - \frac{360^\circ}{N} (35R^4 - 84R^5 + 70R^6 - 20R^7) \quad (11)$$

$$\text{where } R = (\theta_2 - \theta_{20}) / (360^\circ - 2\theta_{20}).$$

Eqs. (9)-(11) are in the proper form to synthesize the slots on the Geneva wheel for the cycloidal, 3-4-5 polynomial, and 4-5-6-7 polynomial cases respectively.

Equations Defining Slot Centerline

Now consider the arrangement shown in Fig. 3 where the $x_1 y_1$ reference system is fixed and non-rotating. The $x_2 y_2$ system rotates with the driving link at a constant rate and the center of the driving pin is located a distance R_2 along the x_2 axis from the point O_2 . If the center distance $O_2 O_3$ is called D , then the position vector of the center of the driving pin is given by

$$\bar{R}_c = D \hat{i}_1 + R_2 \cos \theta_2 \hat{i}_1 + R_2 \sin \theta_2 \hat{j}_1. \quad (12)$$

In order to find the path traced by the center of the pin in the driven member, note that

$$\begin{aligned} \hat{i}_1 &= \cos \theta_3 \hat{i}_3 - \sin \theta_3 \hat{j}_3 \\ \hat{j}_1 &= \sin \theta_3 \hat{i}_3 + \cos \theta_3 \hat{j}_3 \end{aligned} \quad (13)$$

so that the $x_3 y_3$ coordinates of the pin are given by

$$\begin{aligned} x_3 &= D \cos \theta_3 + R_2 \cos (\theta_2 - \theta_3) \\ y_3 &= -D \sin \theta_3 + R_2 \sin (\theta_2 - \theta_3) \end{aligned} \quad (14)$$

When θ_2 is chosen and θ_3 is calculated from one of the standard motion programs (Eq. (9)-(11)), then Eq. (14) can be used to define the slot centerline to generate the proper angular rotation relationship between θ_2 and θ_3 .

Because the selected motion programs are known to have desirable characteristics, the final result should be more satisfactory than the motion which would result if straight slots had been used.

Dwell Recesses and Retainers

The dwell arcs are shown in Fig. 1. The recesses, defined by these arcs, allow the Geneva wheel to be locked by the dwell retainers located on the driver. The depth of these recesses can be arbitrarily chosen within certain limits [10].

Fig. 4 shows the geometry used to determine the radius of the dwell

retainers and depth of the recesses. These angles are affected by the amount of topland left behind on the Geneva wheel. This factor significantly effects the radius and depth of the other two parameters. As shown in Fig. 4a, the arc length of one pin radius (RPIN) was added to each side of the slot. This is the minimum arc length that will be added. This topland is left to ensure that the slot and the dwell recess do not interfere with one another. Considering each of these factors together, the following equations result:

$$STD = 360/(2*N) \quad (15)$$

$$A1 = -\theta_{3_0} + 360/N \quad (16)$$

$$AD3_0 = A1 - 2*RPIN/R_3 \quad (17)$$

$$RD2^2 = R_3^2 + D^2 - 2*R_3*D*\cos(AD3_0) \quad (18)$$

$$AD2_0 = \sin^{-1} [R_3*\sin(AD3_0)/RD2] \quad (19)$$

From this point, it is a simple matter to calculate the dwell arcs. Fig. 5 shows the necessary angles and lengths to be calculated. The equations are:

$$RD3^2 = RD2^2 + D^2 - 2*RD2*D*\cos(180-B1) \quad (20)$$

$$AD3 = \sin^{-1} [RD2*\sin(B1)/RD3] \quad (21)$$

$$DWX3 = RD3*\cos(AD3) \quad (22)$$

$$DWY3 = RD3*\sin(AD3) \quad (23)$$

Values of DWX3 and DWY3 define the X,Y coordinates of the dwell arcs in the rotating x_3y_3 system.

Driver Calculations

The driver consists of two basic parts: the driving arms and the dwell retainers. The angular relationship between the arms and retainers depend upon the type of mechanism. As defined by Bagci [6], a Geneva mechanism is a Regular Geneva if the driving arms are all of the same length and have the same angular spacing between them. Bagci [6] also defined Partially Irregular and Irregular Genevas. Partially Irregular Genevas have driving arms of the

same length but have different angular spacing between them. Finally, Irregular Genevas have driving arms with different radii and the angular spacing between them is also different. The GENSYN software package is programmed to handle the Regular and Partially Irregular Genevas. Therefore, the following discussion will be concerned with these two types.

As the driver rotates, only one of two different events can occur. There will either be motion or dwell. The angular combination of these two events must add to 360 degrees. The "motion" of the driver is the angle swept out by a driving arm from the time it enters a slot until it leaves the slot. The total motion swept by all the driving arms is given by:

$$\text{Total Motion} = \text{PIN} * (360 - 2 * \theta_{20}) \quad (24)$$

PIN.....Number of pins on the Driver

θ_{20}Starting angle of θ_2

The rest of the 360 degrees must be made-up of dwell. Therefore, the dwell is defined as:

$$\text{Total Dwell} = 360 - \text{PIN} * (360 - 2 * \theta_{20}) \quad (25)$$

It should be noted that the total motion and total dwell must be calculated for each new mechanism even though the number of slots and pins remains the same. The reason for this is that the driver and Geneva wheel do not interface at right angles. This is in sharp contrast to the radial slotted mechanisms found in the literature [11,12,13]. The purpose stated for this right angle interface was to reduce the shock effects when the pin entered and exited the radial slots. However, the situation is very different when using curved slots. The curvature takes into account the interface angle and adjusts itself to maintain finite values of jerk at the end points. Therefore, the restriction to maintain a right angle interface no longer needs to be satisfied.

The angular orientation can now be defined since the total motion and

total dwell are known. Fig. 6 shows a Partially Irregular Geneva driver arrangement. Recall the difference between Regular and Partially Irregular was the dwell between the pins. A Regular Geneva can be thought of as a special case of the Partially Irregular Geneva where the dwell between the pins was chosen to be equal. The motion for each driving arm will be the same regardless of the type of mechanism chosen. The following equation defines each motion as:

$$\text{Motion} = \text{Total Motion}/\text{PIN} \quad (26)$$

The dwell between each pin for a Regular Geneva is given by:

$$\text{Dwell} = \text{Total Dwell}/\text{PIN} \quad (27)$$

For a Partially Irregular Geneva, the designer must specify the dwell between the pins. However, the total dwell specified must equal the total available dwell.

COMPUTER IMPLEMENTATION

In the past two sections, the need and theoretical basis for the GENSYN computer synthesis package have been developed. Now consider the details of the program itself. Four basic questions need to be answered:

- (1) What hardware is needed to run the program?
- (2) How is the program organized?
- (3) What are the proper definitions of the input parameters?
- (4) What kind of output results can the user expect?

Each of these questions will be addressed in turn.

Hardware Required

GENSYN is written in Advanced BASIC and is designed to run on the IBM-AT. The computer configuration needs to have 640K memory, one disk drive, color graphics adapter and a printer. The large memory is required so that a virtual disk of 420K can be designated. The virtual disk provides the necessary storage to animate the Geneva wheel and driver. The program will

run on the IBM-PC with the exception of the animation. Obviously, if the IBM-PC is used there is no need to designate the virtual disk.

Program Layout

The GENSYN package is broken down into three separate programs. The three programs are Main, Regular, and Partially Irregular. Once the Main program is loaded, access to the other programs is obtained from the Main program as specified by the user. The Regular and Partially Irregular programs are identical except for the dwell specifications in the Partially Irregular program. Therefore, the following discussion will directly apply to both programs.

The user is given a choice of output displacement functions and then allowed to enter several defining parameters. The program displays a schematic representation of the mechanism and offers the user an opportunity to enter new data. If the user accepts this mechanism, then the program goes to the main menu. From this menu there are three ways to obtain various forms of output. The user can display the mechanism, see graphical representations, or printout the calculated values. With any of these choices the user will ultimately return to the main menu. Access to the start of the program can then be chosen and the whole process can be repeated.

Definition of Input Parameters

The user will be prompted to input several parameters at the start of the program. A complete understanding of these parameters will save considerable time and frustration. The following list will serve to define these parameters:

Number of Slots	The number of slots to be implemented on the Geneva wheel.
-----------------	--

Number of Pins	The number of pins on the driver. This is the same as asking for the number of driving arms.
Radius of Pins	Self-explanatory.
Center Distance	The distance between the rotating centers of the Geneva wheel and driver.
Radius of Driver	This defines the length of the driving arms on the driver.
Starting Angle	This angle is measured from a zero degree reference to a radial line extending from the rotating center of the Geneva wheel. This line intersects the wheel's circumference and slot entrance point simultaneously. This angle is shown in Fig. 2 as θ_3 .

For the most part, the parameters listed are straightforward. However, the value of the Starting Angle (SANG) might cause confusion without further explanation. Although not called by this name, Bin [7] discussed the proper choice of the SANG and its affect on the slot's curvature. The results of his efforts showed that if the SANG was chosen to equal the STD angle, the entrance and exit points would be the same point on the circumference of the Geneva wheel. Increasing SANG would widen the mouth of the slot. If SANG was chosen too large, the exit point of one slot would coincide with the entrance point of an adjacent slot. Going to the other extreme will produce a usable slot. But the driving pin will be at the exit of the slot when the Geneva wheel is in the starting position. Therefore, from these results it is prudent to select SANG slightly larger than the STD angle, but less than $2 \times \text{STD}$.

Results Generated

The program offers the user three types of output. They are displays, graphs, and calculated values. The display menu allows the user to see the mechanism in its initial position, rotated through 360 degrees in incremental steps, or animated. If the user spots an interference problem between the topland on the wheel and the dwell retainer on the driver, a separate dwell wheel can be generated to eliminate the interference. This will be demonstrated in the EXAMPLE section. The angular displacement, velocity, acceleration, and jerk (S-V-A-J) graphs provide the user with the kinematic relationships between the Geneva wheel and the driver. The graphs further emphasize the finite or zero values of jerk at the endpoints of the motion. Finally, when a mechanism has been chosen a printout of the necessary calculated values is available to the user. All of the above output will be demonstrated in the EXAMPLE section.

EXAMPLES

The examples will highlight some of the important features of the program. Three different examples have been chosen. Example 1 shows how to circumvent topland-dwell retainer interference. Example 2 shows the need to use a separate dwell wheel. Finally, Example 3 demonstrates a multiple pin driver.

Example 1

The first example, Fig. 7, is a 4 slotted Geneva wheel mechanism, also referred to as a Maltese Cross [10]. To define this mechanism, the user would first specify that a Regular mechanism was desired. The next decision for the user would be to choose an output displacement function (ODF). In this case, a 3-4-5 Polynomial ODF was chosen. Table 1 lists all the input parameters needed to define the mechanism in Fig. 7. Upon inspection of the mechanism,

there appears to be a problem. The topland on the Geneva wheel may be too wide to fit between the dwell retainer on the driver. The user could use the display menu in the program to rotate the mechanism and confirm whether or not the problem exists. In this case, there is interference. Therefore, the user would need to modify the mechanism. This can be done in one of two ways, either by changing some of the input parameters or by using a separate dwell wheel. If the second approach was chosen, the mechanism would take on the form shown in Fig. 8.

To properly interpret Fig. 8, the reader should be aware that two different planes are being shown. The light colored dwell wheel on the Geneva wheel and the light colored dwell retainer on the driver are in the same plane. The Geneva wheel itself, along with the centerlines, and the driving pins are in a separate plane. In fact, if this picture were true the centerlines would not be visible through the separate dwell wheel.

Returning to the mechanism itself, notice how the separate dwell wheel's topland has been narrowed. Also note the radius of the dwell wheel is less than the radius of the Geneva wheel. The combination of these two factors cause an increase in the dwell retainer radius. This in turn provides more space in the opening of the dwell retainer. The ultimate effect of these changes eliminates the interference problem. This example may imply that the user will always have a choice about using a separate dwell wheel. However, often times the Geneva wheel radius is greater than the center distance specified by the user. In these cases, the driver and Geneva wheel must operate in two different planes and therefore require that a separate dwell wheel be used. This situation occurs in the next example.

Example 2

This example will concern itself with the Geneva mechanism shown in Fig.

9. This Geneva is classified as a Partially Irregular mechanism; note the spacing of the driving arms. The second column in Table 1 shows the input parameters used to define the mechanism's characteristics.

This seven slotted Geneva was chosen for two reasons. First, a separate dwell wheel had to be used in this mechanism. The Geneva wheel radius was larger than the center distance. Therefore, the Geneva wheel and driver could

TABLE 1
Defining Parameters for Examples

INPUT PARAMETERS	Example #1	Example #2	Example #3
Type of mechanism	Reg	Part Ireg	Part Ireg
Type of ODF	3-4-5 Poly	4-5-6-7 Poly	Cycloidal
Number of slots	4	7	4
Number of Pins	1	2	3
Radius of Pins r_2	10	10	
Center Distance	200	200	200
Radius of Driver	165	115	170
Starting Angle θ_3	52	33	55
Dwell:			
between pin 1-2	--	40	30
between pin 2-3	--	--	30
between pin 2-1	--	20	--
between pin 3-1	--	--	0

not operate in the same plane. The input parameters, Radius of Driver and Starting Angle, combine to create this situation. This is a common occurrence for a Geneva mechanism with a large number of slots. As the number of slots increase, the Starting Angle parameter will naturally be a smaller value. This choice of Starting Angle makes the Geneva wheel radius more sensitive to the driver radius. Regardless of the reasons, this mechanism requires a separate dwell wheel. Second, the dwells between the pins are different. Recall, this is a Partially Irregular Geneva and as such, the dwell between each index can be different. The user has chosen 40 degrees dwell between pins 1 and 2 and 20 degrees dwell between pins 2 and 1. Table 1 lists these dwells. Fig 9 clearly shows the dwells and their affects on the driver.

For this mechanism, the user selected a 4-5-6-7 polynomial ODF. The important effect of choosing this ODF is that the angular jerk is zero at the end points. Fig. 10 shows the graphical relationship between θ_2 and θ_3 .

Example 3

The mechanism shown in Fig. 11 will be the third example. Again, Table 1 lists the input parameters used to define the mechanism. In this case, the user selected a Partially Irregular Geneva with the cycloidal ODF.

This Geneva was selected to demonstrate the fact that dwell does not have to be placed between each pin. The total dwell in one revolution of the driver is 60 degrees. How to distribute that dwell is completely up to the needs of the user. In this case, 30 degrees was placed between pins 1 and 2, 30 degrees between pins 2 and 3 and zero degrees between pins 3 and 1. As should be expected, when pin 1 is entering the Geneva wheel, pin 3 is just at the exit point. This causes the Geneva wheel to rotate continuously through two indexes.

Each mechanism can be complimented with a complete parameter listing of both input and calculated values. Fig. 12 is the listing for the mechanism

shown in Fig. 11. To obtain all the values listed on the printout sheet, one additional value was needed. The driver's angular velocity was required so that the extreme values of the S-V-A-J parameters could be calculated.

CONCLUSION

The program GENSYN was developed in response to a need for a computer synthesis package synthesizing Geneva mechanisms with finite angular jerk. The program provides a means to efficiently design Geneva mechanisms from parameters submitted by the user. The results of the input parameters are displayed and decisions can be made whether to accept or reject the design. After a "good" mechanism is designed, a complete listing of the results can be obtained. The animation capability of the program is of considerable value in selecting a final design.

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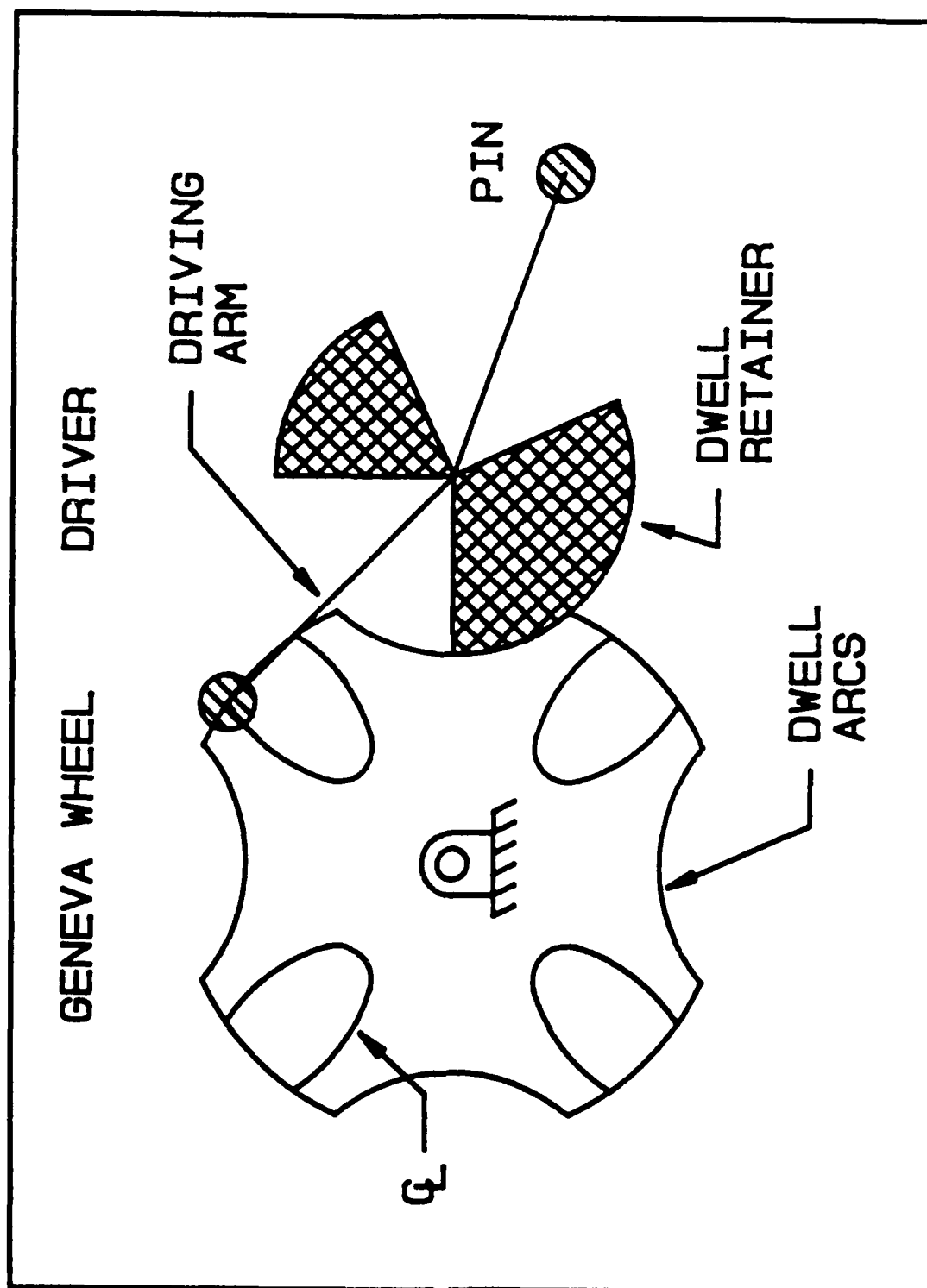


FIGURE 1

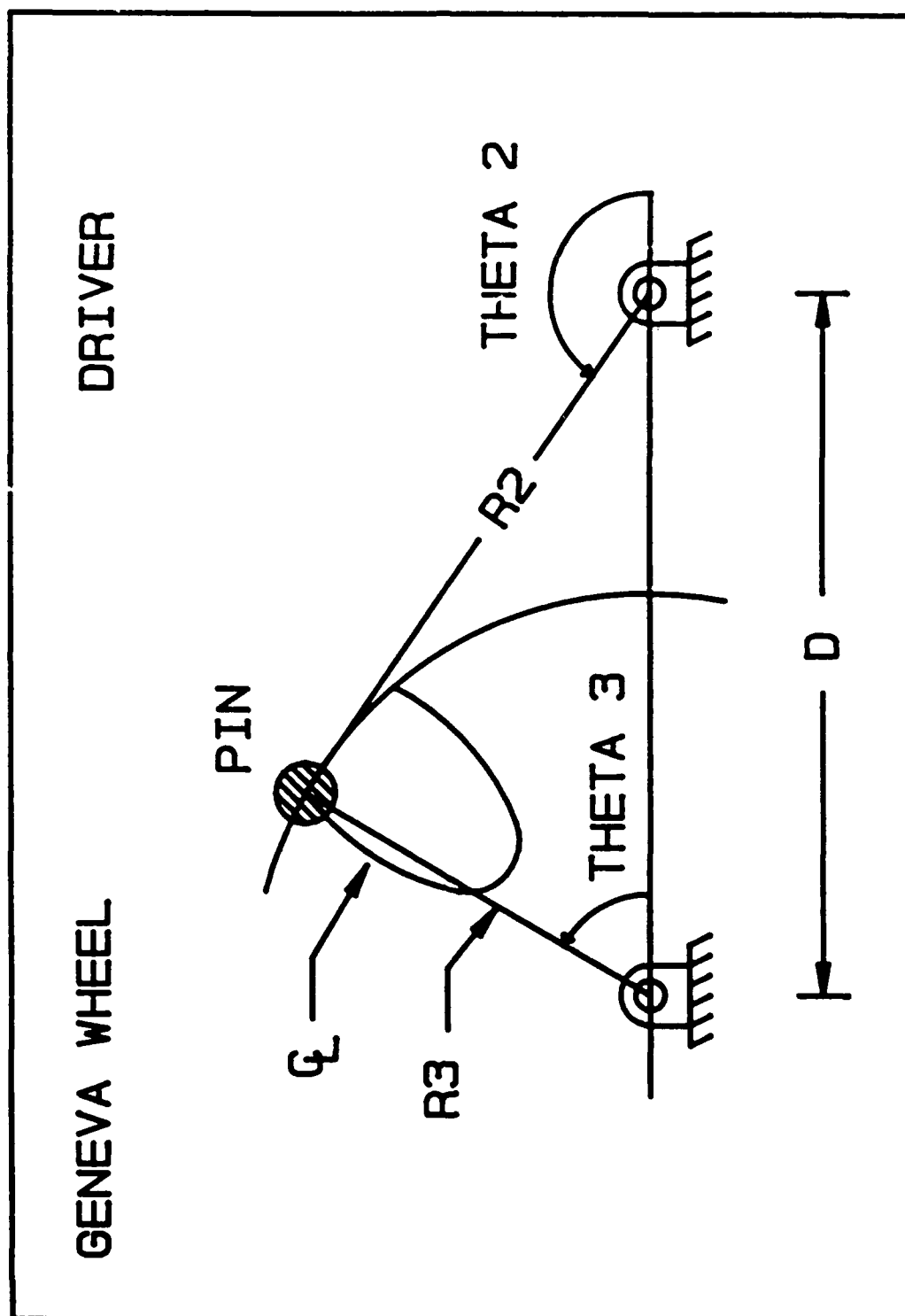


FIGURE 2

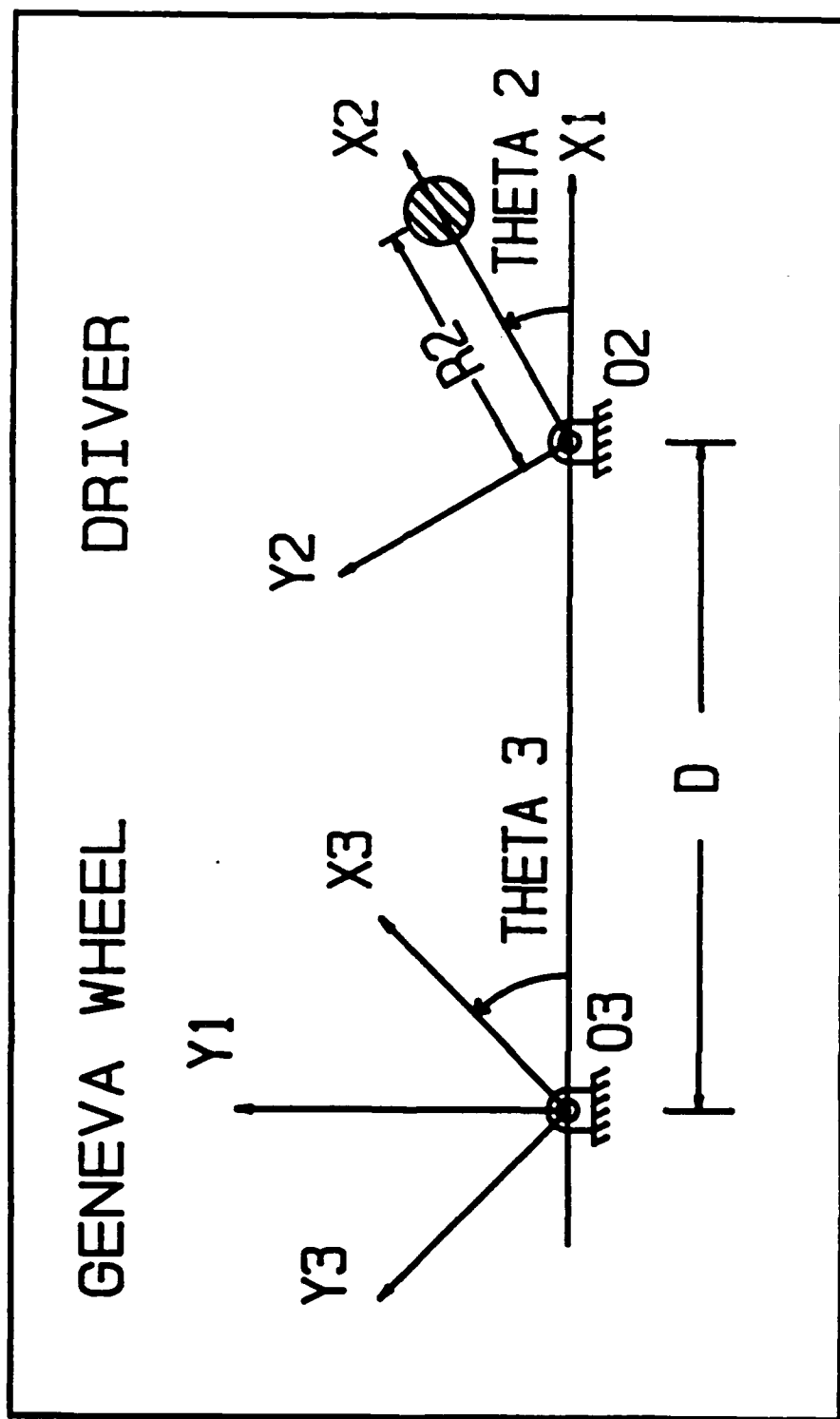


FIGURE 3

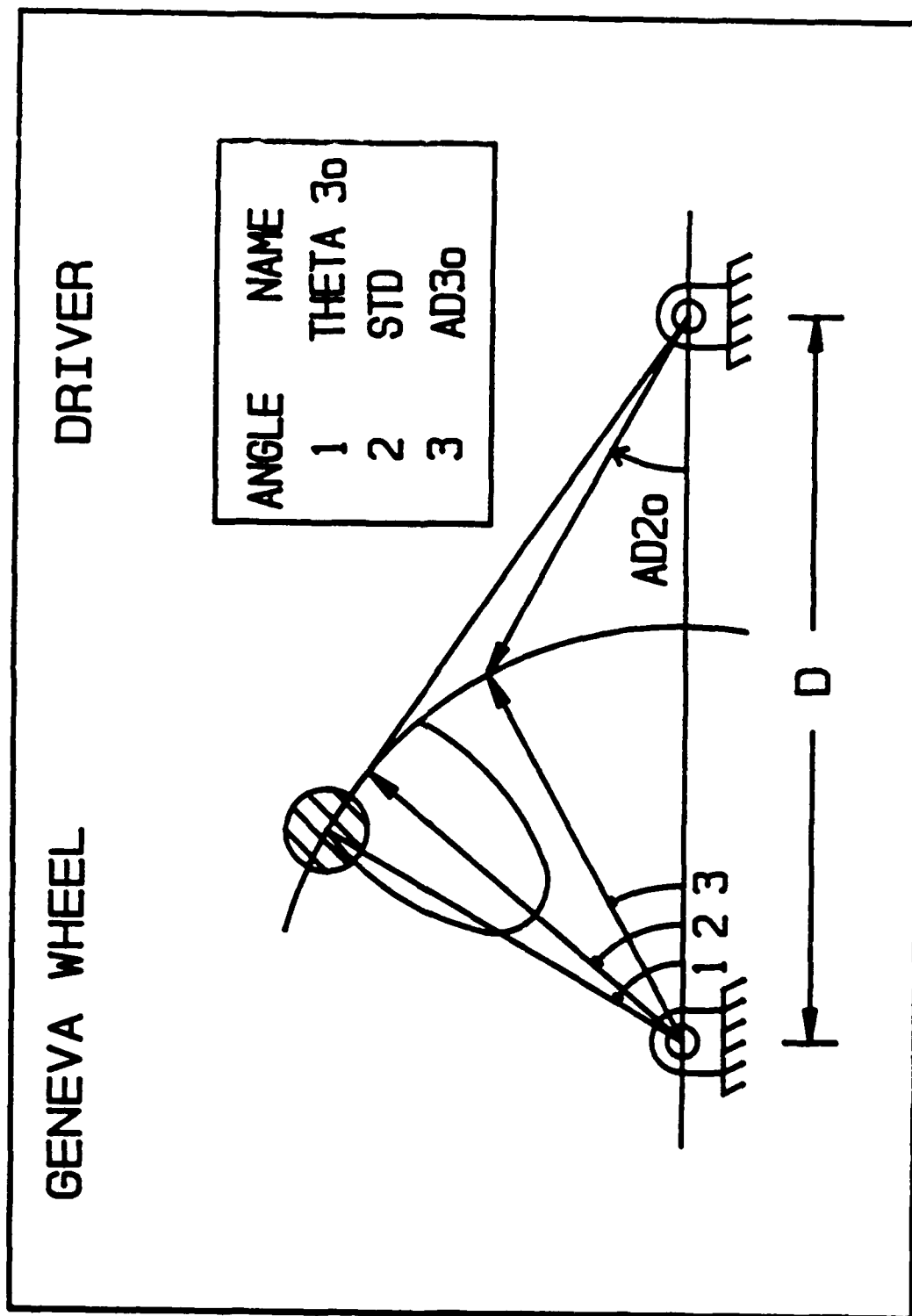


FIGURE 4

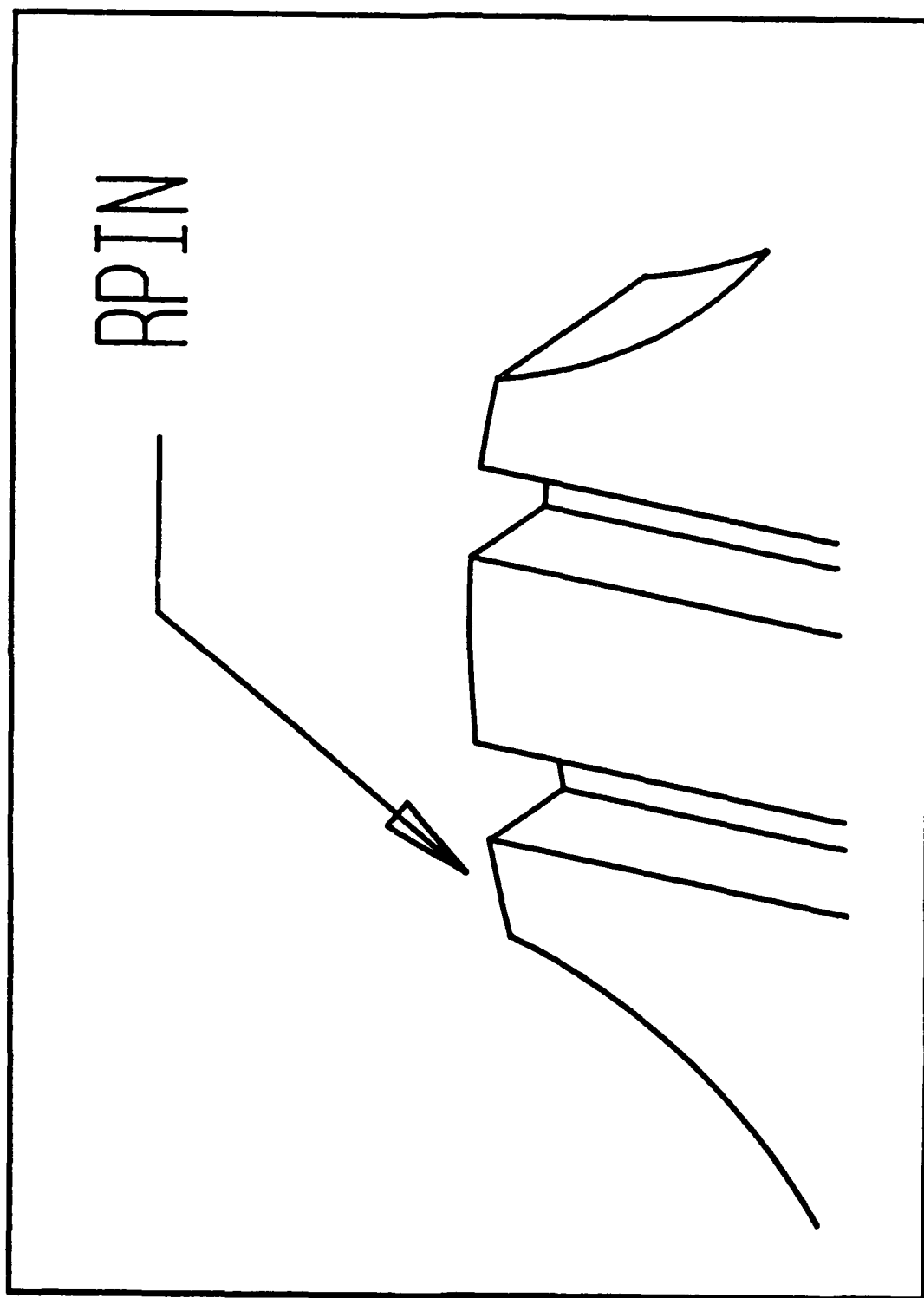


FIGURE 4a

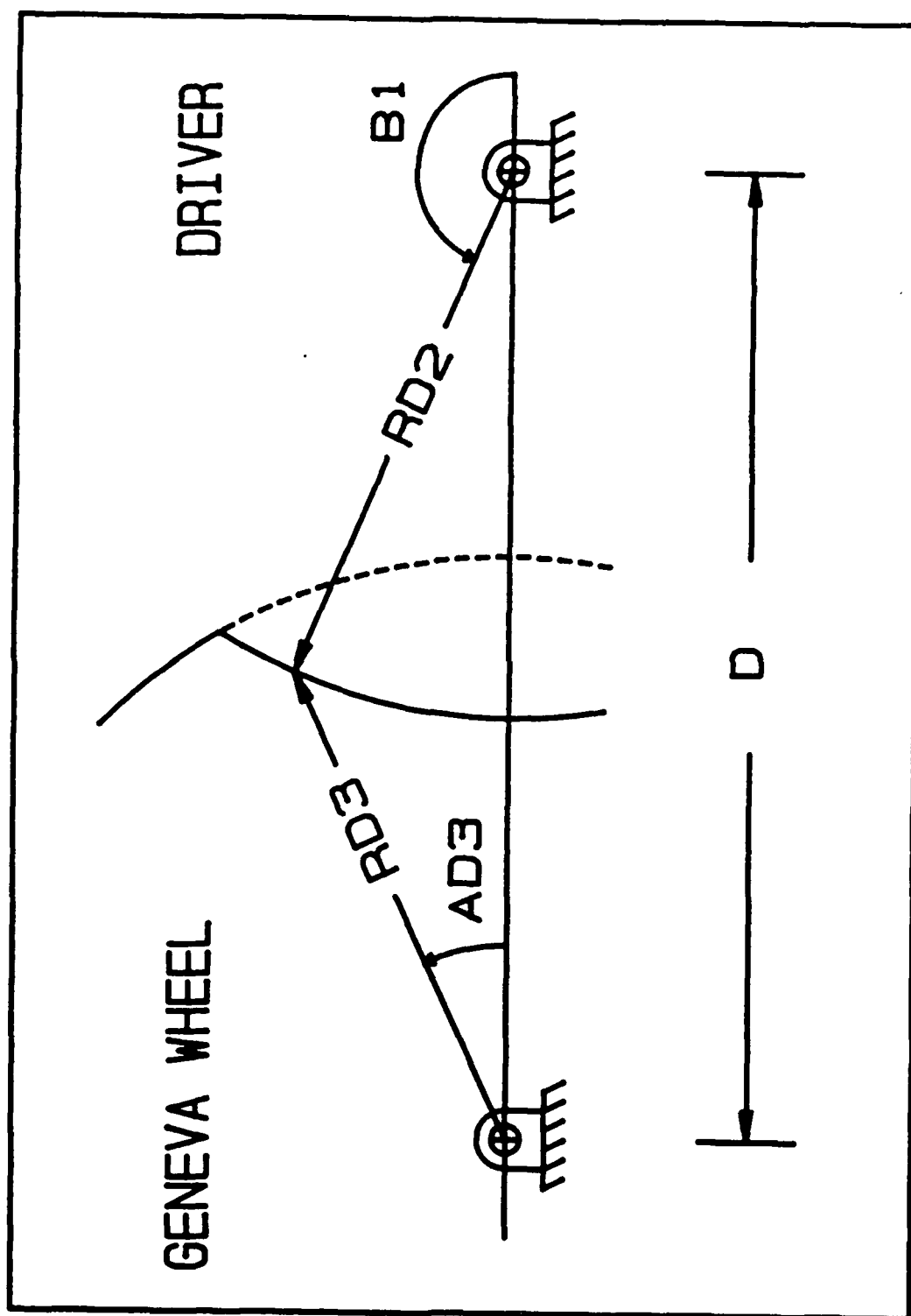


FIGURE 5

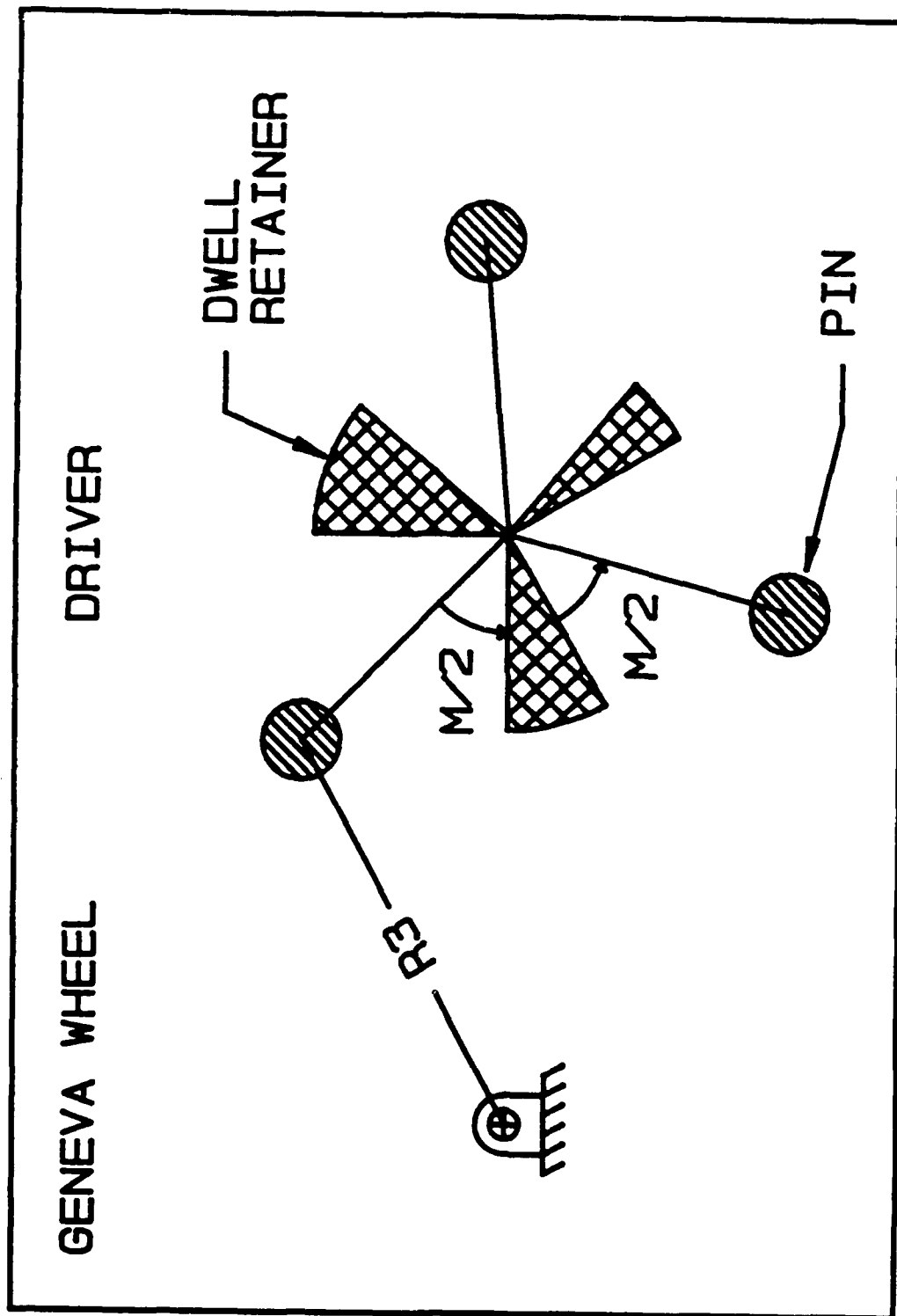


FIGURE 6

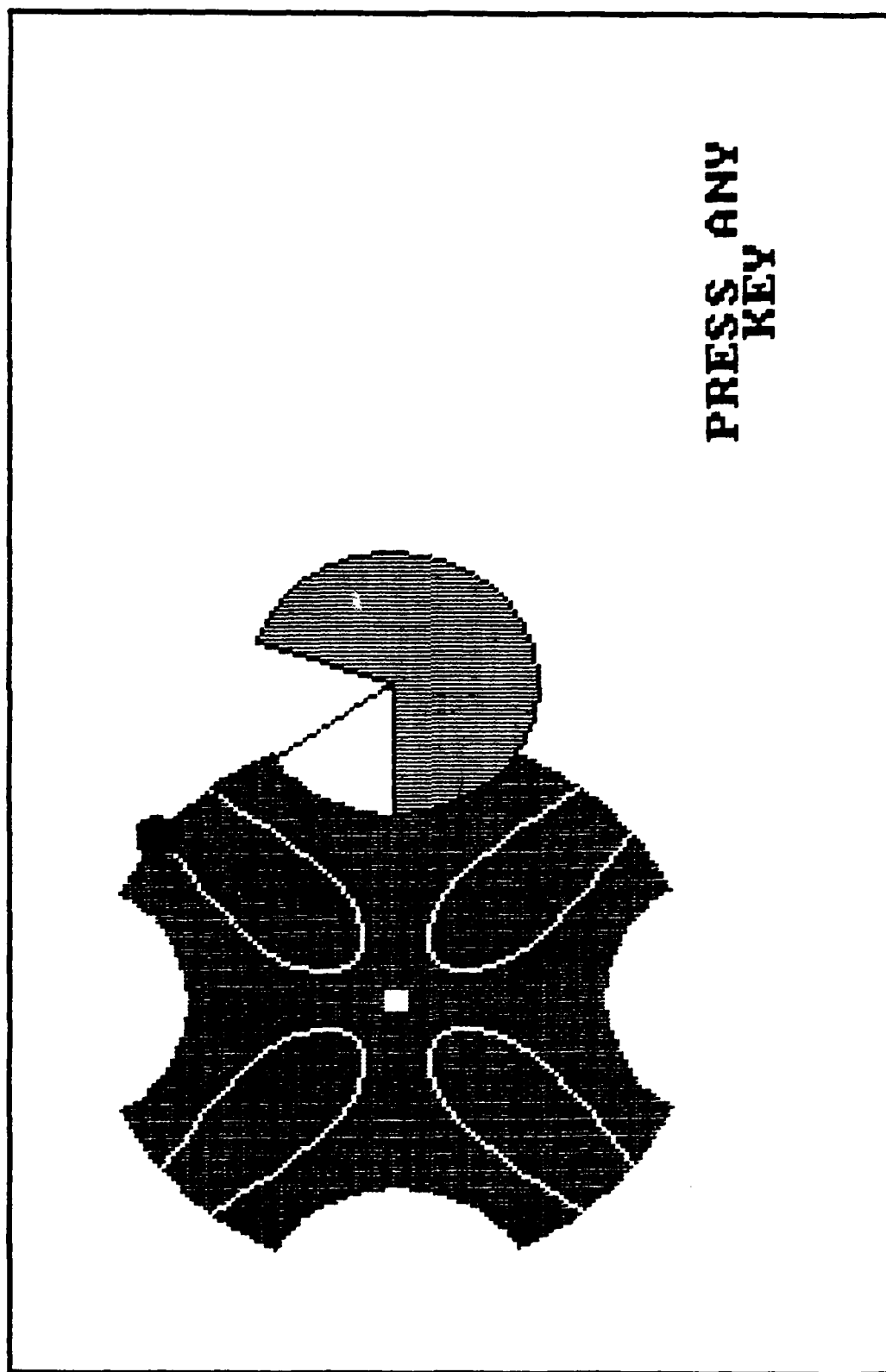


FIGURE 7

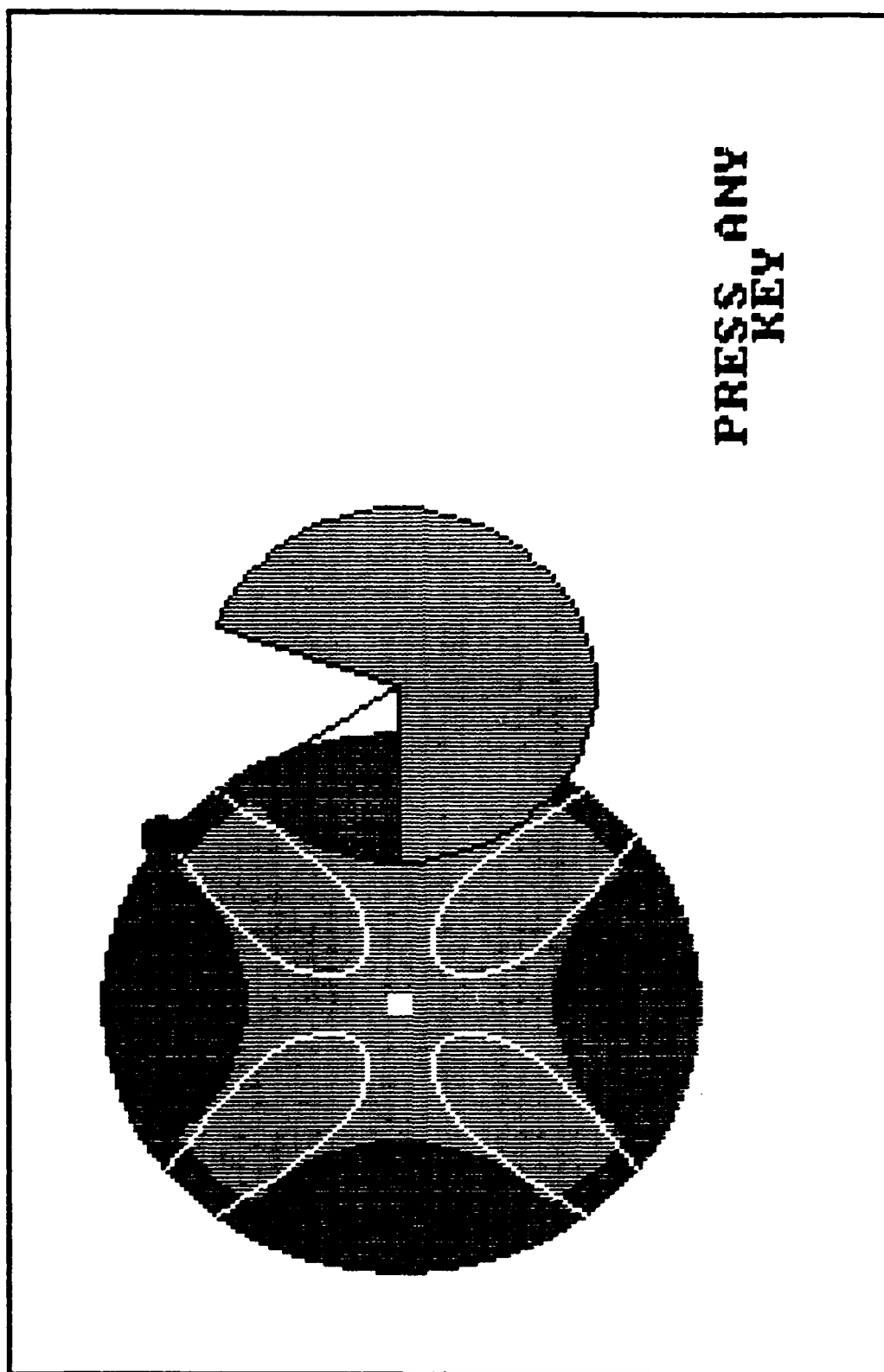


FIGURE 8

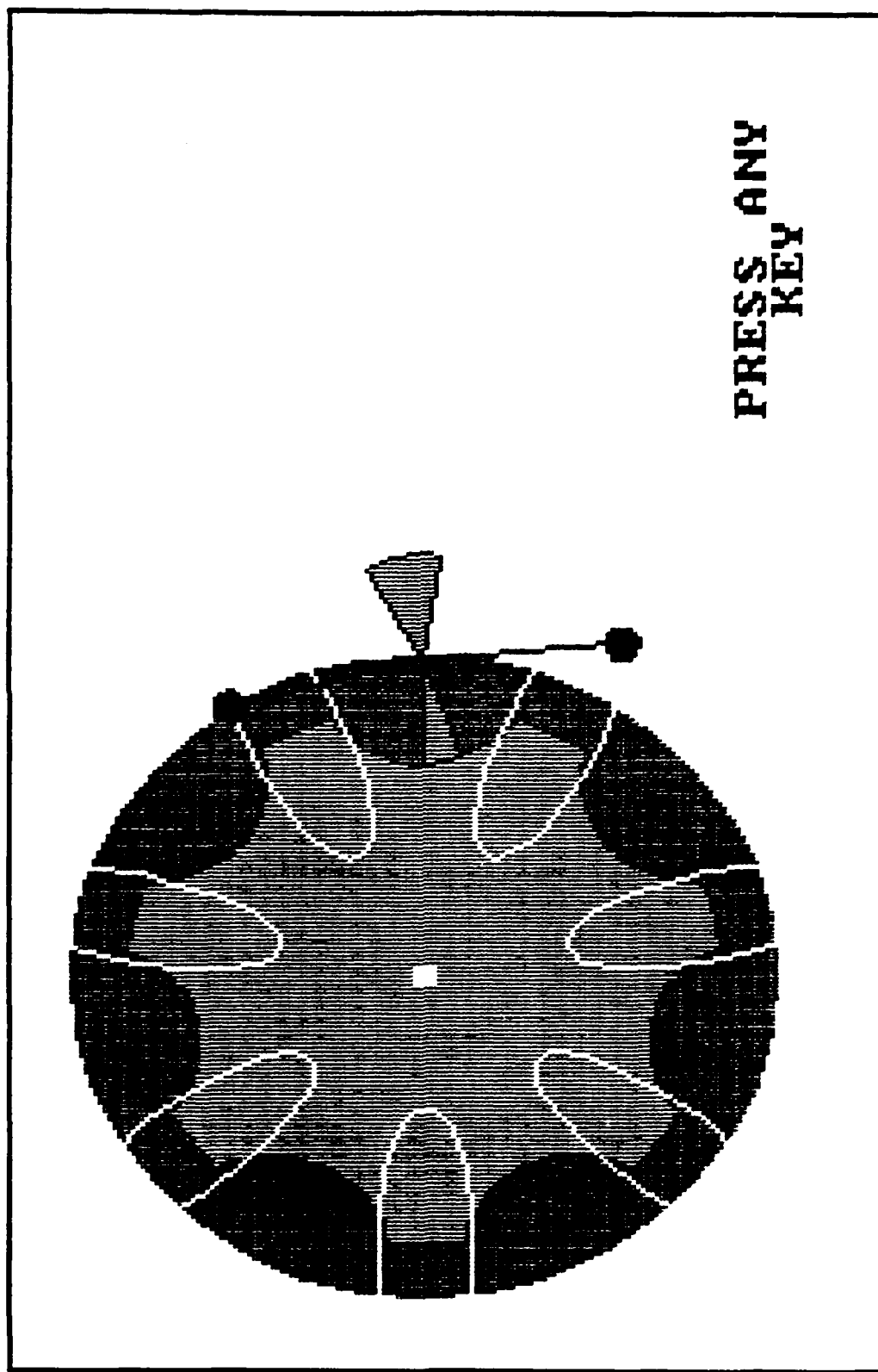


FIGURE 9

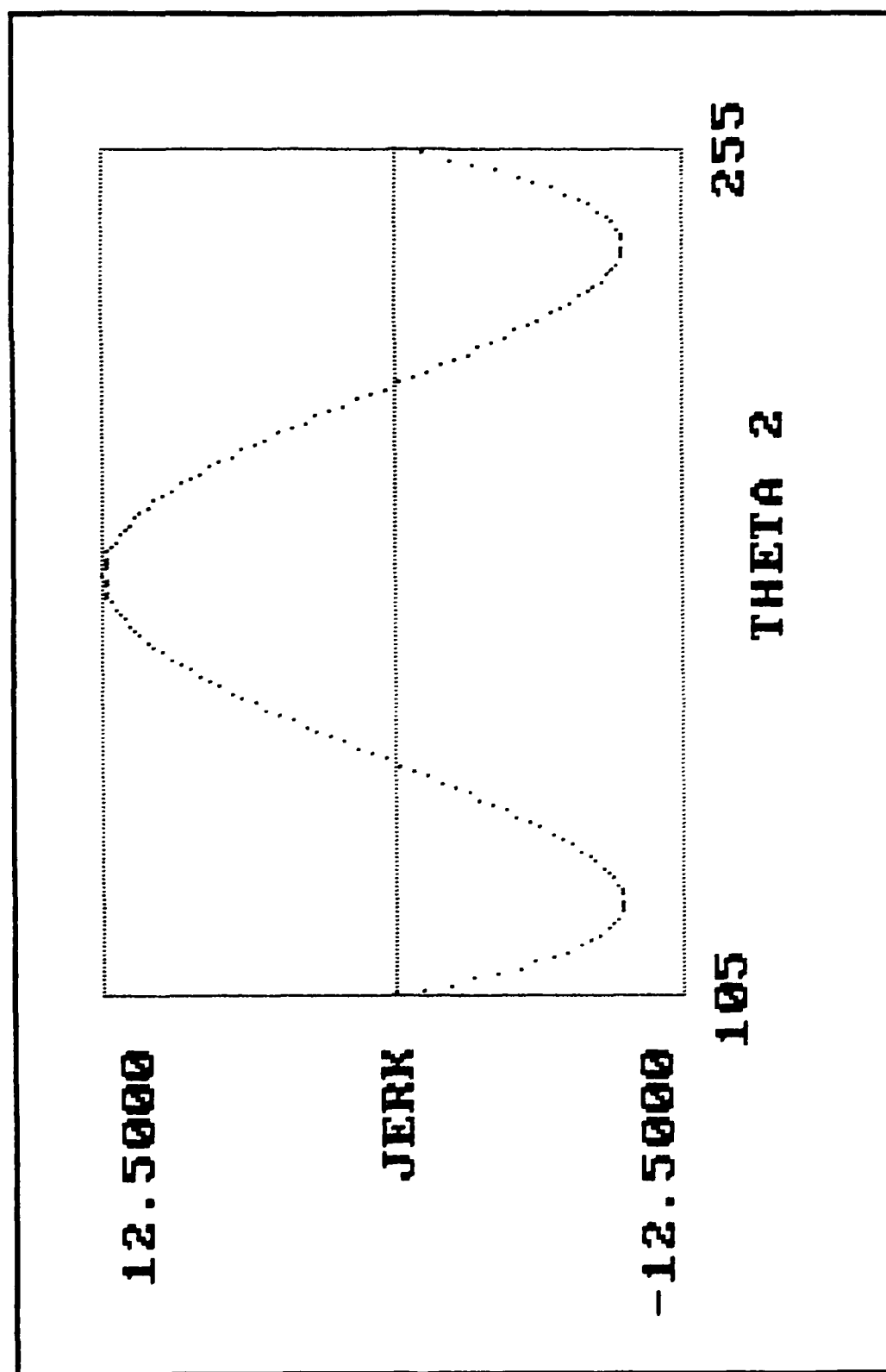


FIGURE 10

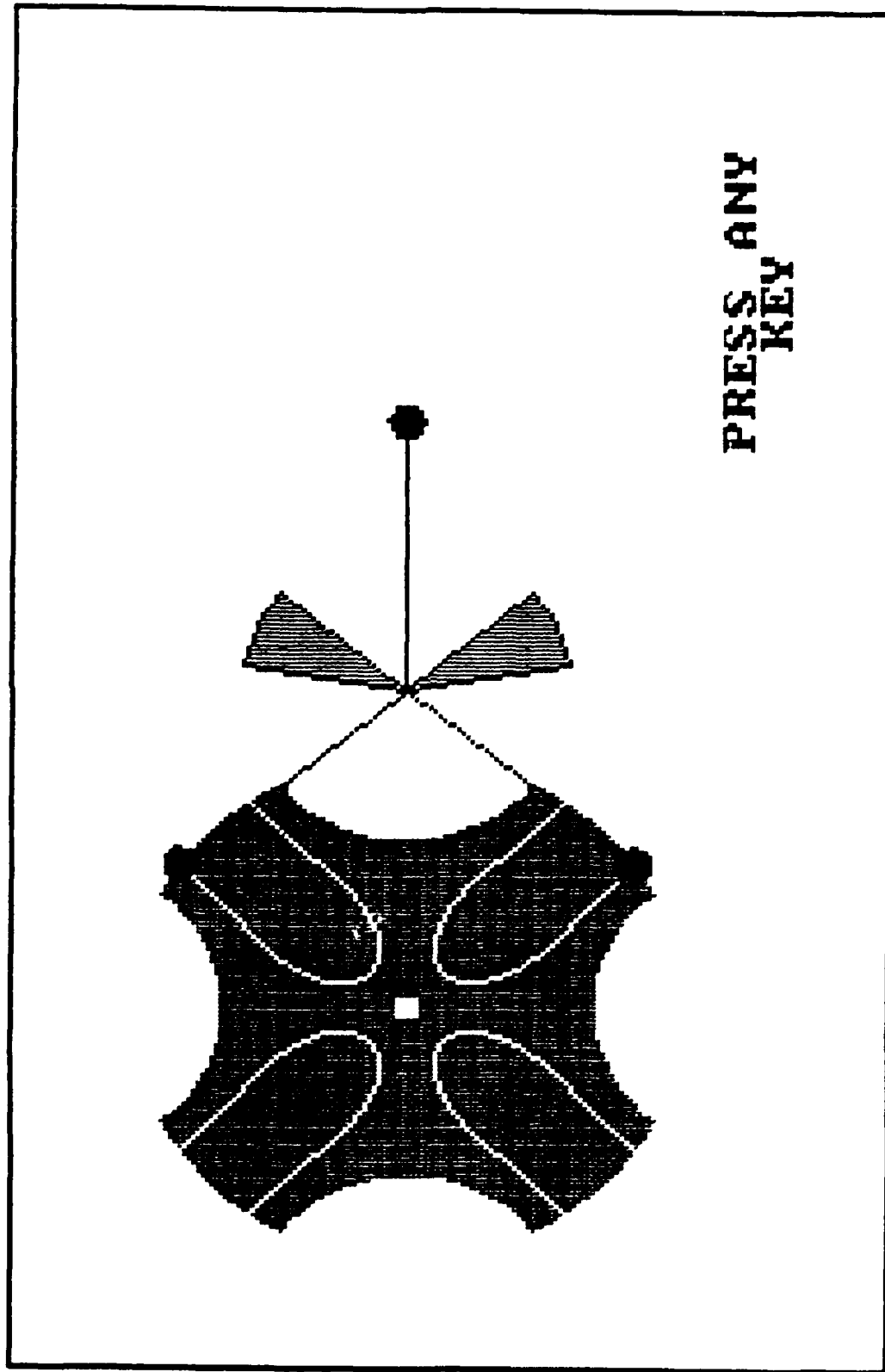


FIGURE 11

PARAMETER LISTING

TYPE OF GENEVA.....PARTIALLY IRREGULAR
 OUTPUT FUNCTION.....CYCLOIDIAL

NUMBER OF SLOTS..... 4
 NUMBER OF PINS..... 3
 RADIUS OF PINS..... 10
 CENTER DISTANCE..... 200

STARTING ANGLE (THETA 3)..... 55
 STARTING ANGLE (THETA 2)..... 130
 ENDING ANGLE (THETA 3).....-35
 ENDING ANGLE (THETA 2)..... 230

RADIUS OF GENEVA WHEEL..... 158.6135
 RADIUS OF DRIVER..... 169.6097

RADIUS OF DWELL ON DRIVER..... 94.24123

DWELL SELECTION:

DWELL BETWEEN PIN 1 & PIN 2 30
 DWELL BETWEEN PIN 2 & PIN 3 30
 DWELL BETWEEN PIN 3 & PIN 1 0

DRIVER VELOCITY..... 25
 ANGULAR DISPLACEMENT..... 90
 MAX(+) ANGULAR VELOCITY..... 0
 MAX(-) ANGULAR VELOCITY.....-45
 MAX(+) ANGULAR ACCELERATION... 35.34292
 MAX(-) ANGULAR ACCELERATION...-35.34292
 MAX(+) ANGULAR JERK..... 55.51654
 MAX(-) ANGULAR JERK.....-55.51654

TOTAL MOTION..... 300
 TOTAL DWELL..... 60
 INDEX RATIO..... 0.200

FIGURE 12

VITA

Jeffrey E. Edmison [REDACTED] S. He received his elementary education in Fairfield and then moved to Salem, Missouri where he attended the Salem Junior and Senior High School. He received a Bachelor of Science degree in Mechanical Engineering from the University of Missouri-Rolla in May of 1987 and was commissioned a Second Lieutenant in the United States Air Force in August of the same year. He is currently enrolled in Graduate School at the University of Missouri-Rolla in pursuit of a Master of Science degree in Mechanical Engineering.